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DEVELOPMENT OF A SHUTTLE PLUME RADIATION HEATING INDICATOR

FINAL REPORT

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Section 1

INTRODUCTION

ABST

The primary objectives ~~of this contract~~ were to develop a Base Heating Indicator Code and a new plume radiation code for the Space Shuttle. Additional work included: revision of the Shuttle plume radiation environment for changes in configuration and correction of errors, evaluation of radiation measurements to establish a plume radiation model for the SRB High Performance Motor (HPM) plume, radiation predictions for preliminary designs, and participation in hydrogen disposal analysis and testing for the VAFB Shuttle launch site.

Results of the work were documented in a series of REMTECH reports as each task was completed to provide timely data. This final report summarizes the work performed.

The two most significant accomplishments under the contract were the development of the Base Heating Indicator Code and the Shuttle Engine Plume Radiation (SEPRAD) Code. The major efforts in revising the current Shuttle plume radiation environment were for the Orbiter base heat shield and the ET components in the Orbiter-ET interface region. Other tasks were relatively minor.

The work performed ~~on the contract~~ is summarized in the technical discussion section with references to the documents containing detailed results. The technical discussion is followed by a summary of conclusions and recommendations for future work.

Section 2
TECHNICAL DISCUSSION

2.1 Base Heating Indicator Code

The purpose of the base heating indicator code (Ref. 1) is to provide a convenient method of evaluating the impact of new Space Shuttle trajectories on the base thermal environment.

The code uses trajectory input to evaluate the environment. The trajectory parameters of most importance are time and altitude along with the points for staging and main engine cutoff (MECO). However, 14 other trajectory parameters, 10 of which are engine gimbal angles, are included in the code as optional input to improve results.

The code output consists of a summary page which evaluates the predicted base heating rates with respect to the operational environment. The trajectory is judged to be either: within the operational environment, within the operational environment with warnings, or outside the current operational environment. The summary is followed by detailed convective and radiation rates as a function of flight time and detailed convective rates as a function of the base surface temperature and flight time.

The radiation portion of the indicator code was developed under this contract and the results are described in Ref. 2. This work included two significant additions to Space Shuttle plume radiation prediction methods: an evaluation of engine gimballing effects and an independent model for radiation from reversed gases.

Engine gimballing is a possibly significant variable which was omitted from the current plume radiation modeling procedure. The small and/or relatively short-duration deflections used for the initial roll maneuver and flight corrections are not significant from a heating standpoint, and other engine gimbal conditions resulting from failures are not considered in the standard operational environment. However, engine gimballing was included in the indicator code to warn in the event the engine positions were significantly changed for a significant portion of the trajectory.

Engine gimbal effects were evaluated using bounds represented by the absolute maximum and minimum gimbal angles for flights STS-8, 9, 13, and 14. Radiation predictions for the gimbal angle range represented by the flights showed no significant effects. So the gimbal angles represented by these flight were used to prepare statistical measures of the allowable gimbal angles which were considered to be within the normal operational environment envelope. These limits were then used in the code as the basis for issuing a warning that the gimbal angles were outside the range considered to be normal. In cases for which the warning is issued, a detailed examination of the intended trajectory must be made.

Reversed gases in the base region were shown to be a significant radiation source during measurements on the first five Shuttle flights. The radiation from this source was included in the altitude adjustment function for the SRB plumes because the major effect was seen in the ET base region during first stage flight. However, including the effect as a function of SRB radiation implies that all surface body points have the same view of the reversed gas as of the SRB plume. This was an expedient choice when it was made because there was insufficient time to prepare a more elaborate model, and the SRB radiation level is generally conservative enough to allow this simplification. For application in the indicator code, it appeared to be prudent to begin the development of a more precise model which could properly allocate radiation sources which might respond differently to trajectory conditions. As a result, flight test data were examined to develop a model for the reversed gas radiation, then this radiation source was removed from the SRB altitude adjustment function. This analysis was only performed for the body points used in the indicator code, and it will be necessary to perform the same evaluation to describe other body points which may be added to the indicator code later.

It is anticipated that both the Shuttle base environment and the indicator code will be expanded in the future to include engine failure cases which will cause significant changes in trajectory and engine gimbal conditions.

2.2 Plume Radiation Computer Code

The Shuttle Engine Plume Radiation (SEPRAD) code (Ref. 3) is the latest in a series of evolutionary developments sponsored by NASA/MSFC to improve prediction of radiation transfer from rocket exhaust plumes. Some of the coding was unchanged from the previous version of the program (Ref. 4) which was designed for axisymmetric and three-dimensional gaseous plumes. The new code was developed to adapt to changes in computer technology and improve flexibility. In comparison to the previous code, it decreased intermediate input/output operations which stored intermediate results and increased use of internal memory to significantly reduce the code run time. In addition, the code was particularized to address the problem of Space Shuttle plume radiation which normally involves radiation from three oxygen/hydrogen plumes and two solid propellant boosters.

The code can describe coupled radiation from the normal Shuttle plumes, and the capability to handle oxygen/hydrocarbon plumes was added to allow for possible additional booster engines.

The code continues to use the statistical band model for gaseous radiation with an exponential line strength distribution for combined Lorentz and Doppler line shapes and the modified Curtis-Godson approximation for inhomogenous gas effects. The solid propellant booster plume is modeled as an opaque surface with an axial variation in temperature and emissivity to approximate the plume emittance.

Geometry is described for heat transfer applications using lines-of-sight describing incremental solid angles in a hemisphere over a body point. The length of the lines-of-sight can be automatically limited by conical boundaries defined around the plumes and shading surfaces which are described as any of seven geometric shapes. Several occurrences of each type of plume can be defined based on the assumption that they do not interfere. At each point along a line-of-sight, the properties are usually determined as being in the nearest plume, but some exceptions to this procedure are required because of the large size difference between the SSME and SRB plumes. As a result, limits are coded to separate the SRB and SSME plumes, but these limits can be easily modified if the code is used for other engine arrangements.

2.3 Orbiter Environment Modifications

The operational environment for the Shuttle Orbiter was reviewed in detail to determine if errors could be found. These are usually caused by: errors in the computer input geometry data, transcription errors in preparing tables from the computer output, and failure to use recommended adjustments in SSME rates.

Geometry input errors result from three sources: incomplete surface geometry descriptions, errors in analyzing the geometry and approximating it with available shapes in the radiation code, and typing errors in preparing the computer input. Incomplete geometry descriptions are caused by drawing reproductions which are not to scale and assembly drawings which do not include dimensions of important components and thermal protection coatings. As a part of the work on this contract, data files which were used for the Orbiter environmental prediction were corrected where errors were found, and completely new data input files were generated which correspond to the tables in the environment document (Ref. 5).

Transcription and typographical errors occur as a result of manually transferring the computer output to tables rather than having computer-generated tables. This could theoretically be avoided, but it would be difficult, because the ordering of points over surfaces by the radiation code cannot be made to match the location and order of the selected body points. The only method of avoiding this limitation is to input the location of each body point as a separate surface in the radiation code input. This requires additional geometry analysis and input which may also produce errors.

Recommended levels of radiation for the SSME plumes often differ from the level predicted by the RAVFAC code (Ref. 21) used in plume predictions. This occurs because the RAVFAC model of the SSME plume (Ref. 22) is not an adequate representation of the actual SSME plume from some viewing aspects. The original procedure was to spot check the RAVFAC results for the SSME plume using predictions of the GASRAD code (Ref. 4) which is more accurate for gaseous plumes. This spot check was normally done at one point on a surface to evaluate the differences between the GASRAD and RAVFAC results, and then the RAVFAC results were adjusted, if required, based on the GASRAD data. This procedure was followed in the 1978 version of the environment (Ref. 23), but it was not carried through completely on the 1984 environment. As a result, some of the SSME rates in the environment may not be as accurate as the earlier version.

An evaluation of the 1984 (current) environment (Ref. 5) was made by comparing it with the 1978 environment (Ref. 23) and looking for apparent inconsistent trends. In general, the 1984 environment for the SSME radiation should agree with the 1978 edition because no changes were made in the SSME radiation plume model from 1978 to 1984. However, the SRB plume model was changed from a cone-cylinder, with the cone extending three nozzle radii, to a continuous cone, but the use of the 1978 model was still recommended for the lower wing surfaces. This resulted in generally increased SRB rates between the 1978 and 1984 environment specifications. Comments on the evaluation of the current environment for the orbiter are given in the Appendix.

In addition to the review of the current environment, a new environment was developed for the SSME engine-mounted heat shield (Ref. 6). The engine-mounted heat shield is one of the most thermally sensitive orbiter components, and the geometry was not adequately described in the original environment.

A study was also made for the SSME nozzle wall environment with an SSME failure (Ref. 8) to compare with Flight 51-F which had a premature shutdown of SSME 1 at 345 seconds.

2.4 ET Environment Modifications

Work on the ET operational environment (Ref. 9) included both revisions for current body points and predictions for body points not originally defined. Most of these points were in the ET/Orbiter attachment region. This region generally has low heating rates because of limited view of the plumes, but some of the aft facing surfaces have relatively high rates. The plumbing components in the region can tolerate relatively high rates, but the cable trays, because of limits on wire insulation temperature, cannot.

The first addition to the ET body points (Ref. 10) provided environments for 25 body points which did not previously have a radiation environment specified. The next task (Ref. 11) involved reevaluation of 3 body points previously specified, analysis of 18 additional body points, and a detailed evaluation of the distribution of radiation on the thrust strut which provided the environment at 76 points. Predictions of radiation in the region between the ET and the Orbiter is time consuming because of the extensive details required to model the shapes of all the surfaces which may shade the body points from the plume radiation. Because of the shading, significant gradients exist on many of the components such as the ET/Orbiter thrust strut, so a large number of points must be analyzed to define the region of highest heating.

The environment for some of the aft facing points provided in Ref. 10 were questioned as being inconsistent with the existing environments for the aft facing points on some of the propellant lines between the ET and the Orbiter. An analysis of the conflict indicated that the original environment on the propellant lines had been predicted using a method which provided an average rate over the aft half of the cylindrical lines rather than a method which would predict the peak rate at the aftmost point. If predictions were made at the aftmost point on the propellant lines, the predicted rates were consistent with the rates of Ref. 10. A search was made of all the geometry files thought to have been used in producing the original ET environment to determine which body points had been predicted using the method of averaging the radiation rates over an area. This method was found to have been used for 32 points. Predictions were made giving the detailed rates at exact point locations which were used in determining the average rates presented in the environment. The results of these predictions were reported and compared with the average rates in Ref. 12.

2.5 SRB Environment Modifications

A revision was made in the SRB radiation environment (Ref. 13) to correct errors in the rates for 2 body points on the kick-ring, to provide rates at 18 additional locations on the kick-ring, and to add 6 points on the top (outer radius) of the attach ring. In addition to these corrections and additions, all points on the kick-ring and the attach ring were recomputed to account for the new position of the SRB nozzle exit for the High Performance Motor (HPM). These changes were published (Ref. 14) as Revision A of the SRB base environment.

2.6 SRB Radiation Measurement Analysis

The SRB High Performance Motor (HPM) modification consisted of a small decrease in the nozzle throat and a small increase in the nozzle exit diameter. The modified nozzle is approximately 10-inches longer than the original, and the changes produce small increases in the chamber pressure and nozzle area ratio. It was not expected that these changes would significantly alter the plume radiation, but radiometer measurements made during static tests indicated a large increase in the plume emittance at the nozzle exit. Careful examination of the radiometer data and the effect of nozzle gimballing on the results indicated that the radiometer alignment had changed, so it was actually aimed slightly into the nozzle exit. A request was made that the alignment be checked, and the theory proved to be correct. After the radiometer was properly aligned, the results were consistent with the measurements on the initial SRB nozzle. The results were reported in Ref. 15.

2.7 Preliminary Design Predictions

Plume radiation predictions (Ref. 16) were made to evaluate the thermal radiation for a Shuttle derived vehicle consisting of 3 SRMs similar the the current SRB. Two of the SRMs (Stage 1) were mounted on each side of a third central SRM (Stage 2) which was assembled in-line with a Centaur G (Stage 3) and the payload. Sea-level radiation predictions using the current SRB plume radiation model indicated that the rates on the SRMs at sea-level were less than the corresponding locations on the Shuttle SRBs. However, the rate to the nozzle closure of the central SRM was significant, 17.5 Btu/ft^2-sec.

2.8 Aeroassist Flight Experiment

The Aeroassist Flight Experiment (AFE) is a test vehicle to investigate aerodynamic braking technology for an Orbital Transfer Vehicle. In the initial stage of the AFE development, it was anticipated that a STAR 48 motor would be used for propulsion. A plume radiation model for the proposed AFE motor configuration was derived from a plume radiation model used for the PAM D-II stage. This plume model was then used for to predict the radial distribution of radiation on the vehicle which were reported in Ref. 20.

2.9 VAFB Launch Site Studies

Because of the potential for hydrogen entrapment in the SSME exhaust duct at the VAFB launch site, several tasks were performed. In the first, plume radiation environments were predicted for hydrogen burn-off igniters inside the duct (Ref. 17). This was followed by recommendations for instrumentation for tests of VAFB duct modifications at the MSFC 6.4 percent Shuttle Acoustic Test Facility. The instrumentation recommendations for plume radiation and reversed plume flow out of the duct entrance were documented in Refs. 18 and 19.

Section 3
CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations are directed at methods of radiation prediction and more automated application of those predictions as heat inputs to evaluate thermal protection systems. The current modeling technique for SRM plumes using solid surface models in the RAVFAC code should be improved for future launch systems and the computer output should be designed to go directly into an environment database to be accessed along with aerodynamic heating and convective base heating as input to structural thermal analysis codes. A code should also be prepared which can access the mathematical descriptions of vehicle surface contours to prepare surface input data for radiation codes.

Improvements in modeling large SRM plumes could use empirical data in a more sophisticated surface emittance model or move to a more theoretical basis by using Monte-Carlo prediction techniques to include both gaseous emission and particle emission and scattering. Because of the difficulty in predicting the thermal and optical properties in the plume, it may be necessary to either delay the Monte-Carlo techniques or "calibrate" them with empirical data. An interim technique could use surface emittance models with directional variation of emittance as a function of angle to the surface. In this method the plume description would require measurements of the plume over a range of angles, particularly those in the direction of the base. The current band-model codes appear to be adequate to predict radiation from gaseous plumes, but these also require measurements to assure success because of the uncertainties in predicting detailed plume properties.

The current method of handling the results of the radiation code and combining it with other heating modes and trajectory variables is error prone and incurs increased costs because of excessive manual handling of the data. Generic database designs should be developed to handle all input surface shape descriptions and output heating data. In this way, all codes preparing thermal environment input could be designed for a common output form. Even if modifications of the database are required for a specific vehicle, the coding modifications should not be extensive if good code design is used to hide the ultimate input and output forms.

Section 4
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APPENDIX

COMMENTS ON THE ORBITER PLUME RADIATION HEATING ENVIRONMENT (REF. 5)

TABLE 3 - WING UPPER SURFACE

Many SSME rates (50 out of 65) are lower than the 1978 environment (Ref. 23), while others are exactly the same. With the exception of one point, all rates that appear to be correct are points that had been adjusted to correspond to GASRAD results in 1978. Current RAVFAC results using the data files apparently intended for these surfaces agree with the 1978 RAVFAC predictions. Current predictions of SRB rates indicate less than 0.1 Btu/sq-ft-sec.

The geometry of the wing surface is poorly defined for radiation input purposes, and it is possible that a better description was obtained which is not included in the data files currently available. However, errors appear to be too large to be explained by small changes in surface angle.

TABLE 4 - WING AFT EDGE

SSME rates are about 7-percent higher than Ref. 23 because the GASRAD adjustments to the RAVFAC results were not applied.

SRB rates are inconsistent and possibly in error in three ways. First, the rates indicated for the cone-cylinder plume model are lower than the rates previously published for the cone-cylinder model in Ref. 23. Second, the rate predicted for the DFI instrumentation is inconsistent with the environment in the same vicinity. Finally, use of the cone-cylinder plume model on the aft edge is inconsistent with the statement in the body of Ref. 23 which states that this model is used for the wing lower surface.

TABLE 5 - WING LOWER SURFACE

SRB rates on the trailing edge of the lower surface are significantly higher than Ref. 23. In the data used for Ref. 23, the surface slope became parallel to the Xo axis at the trailing edge rather than continuing the positive slope which exists further forward on the lower surface. The previous (1978) low rates at the trailing edge caused apparently inconsistent trends. This is improved in the current environment, but the reason is unknown. Either the rates were extrapolated from the forward surface, or the geometry was changed.

Use of the 1981 (conical) plume model for the 30-percent span points is inconsistent with the text statement that the 1978 (cone-cylinder) plume model was used for the wing lower surface. This tends to produce a conservative (high) environment.

TABLE 6 - FUSELAGE LOWER SURFACE

The data element which was used for the RAVFAC prediction had points 1851 and 1850 in the same location, but the spanwise gradient is negligible.

TABLE 7 - BODY FLAP

The geometry is confusing, so it is difficult to evaluate in comparison to the 1978 environment. Some points shown at full span in the figure are at 80-percent span in the table, and the only data file available does not correspond to some of the locations.

The recommended GASRAD adjustments to the RAVFAC predictions for the SSME rates were not carried forward from 1978. SSME radiation to points 261 and 239 decreased relative to 1978 by about 22 percent, while points 236, 263, 242, and 243 increased by from 4 to 20 percent.

The SSME altitude adjustment was also omitted for the lower surface, and the adjustment was incorrectly listed for point 263.

TABLE 8 - VERTICAL TAIL

Some of the SSME rates were not adjusted to the rates based on GASRAD predictions, but these are not significant.

The indicated rate on the side-facing DFI would be significantly affected by the radiometer view angle which was apparently assumed to be 180 degrees for the rate shown.

TABLE 9 - BASE HEAT SHIELD

Most GASRAD adjustments to the SSME rates were not carried through from the 1978 environment, but these are generally not significant.

A serious error occurred on the upper heat shield (points 956-964) because of the omission of shading by the upper SSME. As a result, the SSME rates are much too high and a few of the SRB rates (points 956-958) were slightly high.

The environment of the SSME Engine Mounted Heat Shield (EMHS) contained averaged data on the EMHS and lacked the necessary detail in the area of the seal between the EMHS and the heat shield "bulge." The revised environment in Ref. 24 should be used for these components. A detailed explanation of the revised radiation environment is contained in Ref. 7.

The heat-shield "bulge" which accommodates the EMHS was modeled as a sphere rather than a cone. This is not expected to make a significant difference, but no evaluation was made of the effect that the difference in surface angle might have.

TABLE 10 - SSME UPPER ENGINE (NO. 1)

SRB rates for the top of the hat band at X/L=0.410 are in error because of an incorrect radius input (37.8R should have been 39.8R). This causes shading of the cylinder representing the "top" point by the disk representing the "aft" point. There are no errors in the SSME rates because the GASRAD adjusted rates from the 1978 environment were used for this hat-band.

The GASRAD adjusted rates were not carried forward from the 1978 environment at most points. This is not significant in most cases, but it causes the environment to be significantly overpredicted in the high heating region between 225 and 315 degrees.

TABLE 11 - SSME LOWER ENGINE (NO. 2)

Serious typographical error on points 7801 through 7808. SSME rates shown as 10.10 should be 0.10.

All significant GASRAD adjustments to the SSME rates were carried forward from the 1978 environment.

Some of the predicted SRB rates decreased compared to the 1978 environment, although the change in the plume model was expected to cause an increase. The changes were not significant, and the cause of this behavior was not investigated.

TABLE 12 - SSME H2 MANIFOLDS

GASRAD adjustments to the SSME rates were carried through from the 1978 environment, and the SRB rates appear to be consistent except for rates at points 7931 and 7972 which should be similar and are not.

TABLE 13 - OMS NOZZLE

GASRAD adjustments to the SSME rates were not carried through from the 1978 environment and there were insignificant errors in SSME altitude adjustment codes for two points. If the GASRAD adjustments had been used, it would have reduced rates above 6.65 Btu/sq-ft-sec by 10 percent.

TABLE 14 - OMS ENGINE SHROUD

GASRAD adjustments to the SSME rates for the side (points 7700 through 7790 by 10) were not carried through from the 1978 environment. This produced environment rates which are 5-percent below the recommended GASRAD predictions. An exception is point 7730 for which the RAVFAC predicted rate increased from 3.59 in 1978 to 4.19 currently - cause undetermined.

TABLE 15 - OMS POD BASE

GASRAD adjustments to the SSME rates were not carried through from the 1978 environment for the parabolic base, but they were carried through for the trapezoid base. The omission of the GASRAD adjustments generally causes the environment to be conservative with the exception of one point. The SSME rate at point 781 is below the both RAVFAC and the GASRAD predictions. This may be the result of inconsistent geometry for point 781 described below.

Point locations are illustrated and tabulated in Fig. 18a of Ref. 5 and also tabulated in Table 15-1 of Ref. 5. There are some inconsistencies in the locations stated by these sources. The locations of the points closest to the origin illustrated in the figure are not consistent with either of the tables, and the radii shown for points 778 and 781 in the table on Fig. 18a are not consistent with the location given in Table 15-1.

TABLE 16 - OMS/RCS POD

No significant errors noted in the very low rates.

TABLE 17 - RCS POD

GASRAD adjustments to the SSME rates which resulted in rate increases were applied, but those which resulted in rate decreases were not. The large vertical gradient between points 829 and 830 were confirmed by GASRAD predictions, but the GASRAD predicted rates were 10 to 15-percent below the environment.

The SRB rate for the DFI is a little low compared to points in the vicinity.

TABLE 18- 1 THROUGH 18- 6 - RCS NOZZLES 10-12 AND 1-3

GASRAD adjustments to the SSME rates were carried through, but two SSME altitude codes were omitted (points 8600 and 8602).

TABLE 18- 7 THROUGH 18-10 - RCS NOZZLES 4-7

The SRB rates on the nozzle lips are below the values on the surface that the nozzles fire through. There is not enough data on the geometry of the surface to evaluate the correct rates. Input geometry for the surface is at an angle to the Orbiter Xo-Zo plane, but input for the nozzle exit planes is parallel to the Xo-Zo plane.

Typographical errors: 255 degrees should be 225 degrees in all tables and the Yo coordinates for 135 degrees is off by 0.1 in Table 18-7.

TABLE 18-11 THROUGH 18-14 - RCS NOZZLES 8 AND 9

GASRAD adjustments to the SSME rates were omitted for all but one point. This causes a 9 to 10-percent overprediction for some of the higher rates and insignificant changes for lower rates.

Typographical error: 255 degrees should be 225 degrees in Tables 18-13 and 18-14.

TABLE 19-1 AND 19-2 - OMS POD VERNIER THRUSTER

Input geometry for all nodes in the RAVFAC prediction used two elements per node. This causes an averaging of the rates from the two locations. The resulting rate and indicated location are slightly different than would be obtained for the indicated value of theta.